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Multiplicity, activity and fast rotation in early-type stars

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Abstract. There are obvious and direct ways in which the presence of binary companions may affect activity in OB stars through tidal interactions. In this review, however, I consider a more fundamental role for multiplicity and explore claims that the Be phenomenon may be intimately linked to binarity. I describe the binary channel for the formation of Be stars and the ongoing discussion about the relative contribution of this channel to the population of Be stars. I also present evidence suggesting that some environments are more favourable for the appearance of Be stars and explore whether this may be connected to initial conditions, such as the chemical composition or the distribution of rotational velocities on the ZAMS.

1. Introduction

As the presence of binary (or multiple) companions in a close orbit can affect the evolution of a star, it is only natural to assume that it can also have an effect on the occurrence of different kinds of stellar activity. In some cases, the physical mechanisms connecting the presence of a companion with activity are more or less transparent. For example, the tidal force exerted by a companion can excite different kinds of stellar oscillations, as discussed by Willems (2006). Such induced oscillations are believed to occur in a few binaries containing OB stars (e.g., Quaintrell et al. 2003).

Similarly, the tidal force exerted by a companion on the disk of a Be star can result in photometric variability. For example, regularly spaced, small brightenings of the B6 IVe star HR 2968 have been interpreted as due to the presence of a companion (Carrier et al. 1999). However, dedicated searches for periodic photometric variability locked with the orbital period in Be/X-ray binaries have rarely resulted in detections (cf. Roche et al. 1993; Clark et al. 1999), even though the presence of a neutron star in a relatively close orbit suggests that the tidal effect on the decretion disk would be rather strong in these systems (but see Coe & Edge 2004, for examples of positive detections in SMC Be/X-ray binaries). In some Be stars, (quasi-)periodic variations in the shape of emission lines (V/R variability) occur with the orbital period of a companion (see, e.g., Stefl et al. these proceedings). The presence of a companion is one obvious way of providing a clock when a clear periodicity exists.

There are, however, deeper ways in which membership in a stellar system may be connected to activity. Considering the focus of this meeting on the use of active stars as laboratories to study the effects of fast rotation, I will centre on Be stars and explore claims that binarity provides the mechanism to spin

up Be stars to high rotational speeds. Afterwards, I will move to a higher level of multiplicity and discuss the likelihood that membership in an open cluster affects the chances of becoming a Be star. Finally, I will address the role that variations in metallicity may have in the occurrence of the Be phenomenon.

2. Be stars and critical rotation

A relatively important fraction of moderately massive stars display, at least at times, emission lines and a characteristic infrared excess which can be explained in terms of a quasi-keplerian disk of material surrounding an otherwise normal star. These are the Be stars (see Porter & Rivinius 2003, for an up-to-date review). Be stars constitute the largest group of active OB stars. As a class, they are characterised by rapid rotation and therefore represent an excellent laboratory to study the effect of rapid rotation on the evolution of OB stars.

Though emission lines are the most noticeable characteristic of Be stars, we have to stress that not all emission-line stars with B spectral type are Be stars. For example, many interacting binaries display emission lines which are due to flows of material between the two stars or *accretion* disks around one of the components. Likewise, Herbig Be stars display emission lines from a disk believed to be the remnant of the accretion disk through which the star formed. Here we will restrict ourselves to "classical" Be stars, those objects in which emission is believed to arise from a disk of material expelled from the star. Classical Be stars do occasionally lose their disks and are then able to re-form them. We will take this capability to build the disk from the inside as the defining characteristic of a Be star. I will not discuss sgB[e] stars, as the role of rotation or binarity in their activity is unclear, and a major monograph on these objects has just been published (Krauss & Miroshnichenko 2006).

The actual incidence of the Be phenomenon is a matter of discussion (see Section 3.2.). The usual practise is defining the Be/B fraction as the number of Be stars in a population divided by the total number of B-type stars (Be + non-Be). However, considering the large difference in intrinsic brightness between early and late B-type stars, it may happen that a magnitude-limited study of the Be star population in some environment (for instance, an open cluster, or the SMC) does not reach the faintest B-type stars. Because of this, it is also customary to talk about the Be/B fraction down to a given spectral type. This should be remembered when discussing the Be star fraction in open clusters, as there is increasing evidence that Be stars are much more numerous among stars evolved away from the Zero Age Main Sequence (ZAMS) than among stars still close to the ZAMS (see Section 5.). For example, when considering a massive well-populated cluster like NGC 663 (cf. Pigulski et al. 2001), the Be/B fraction is very high if we just count stars earlier than B5, but – given the shape of the IMF – may be rather lower if all the late B-type stars are included.

2.1. Rotation, how close to critical?

The existence of a connection between fast rotation and the Be phenomenon has been widely accepted for a long time (cf. Struve 1931). Be stars are observed to rotate at very high speeds and even these high measured rotational velocities

represent an underestimation of the actual rotational speed Ω because of the effects of gravity darkening (Townsend et al. 2004; Frémat et al. 2005).

Fast rotation reduces the effective gravity on the outer atmospheric layers, perhaps allowing material to be lifted out of the star by effects that would otherwise be only minor disturbances. Such lifting would be extremely easy if the outer layers of the star were rotating at the critical speed $\Omega_{\rm crit}$, at which their velocity would be comparable to the Keplerian velocity. If Be stars rotate at $\Omega_{\rm crit}$ or *very* close to it, then mass ejection can be explained by any mechanism that can supply a small amount of energy or angular momentum to the material.

This idea has recently been explored by a number of authors. Among them, Keller et al. (2001), observing that (as discussed in Section 5.) Be stars in open clusters are almost always restricted to the upper region of their HR diagram, i.e., to relatively evolved stars, and assuming that the development of the Be phenomenon is intimately linked to fast rotation, interpret this fact as evidence for an evolutionary effect. They note that the evolutionary models of Meynet & Maeder (2000) for stars in the range $\sim 5M_{\odot} - 15M_{\odot}$ predict that the ratio $\Omega/\Omega_{\rm crit}$ will increase as the stars evolve. As a consequence, even though a few very fast rotators may become Be stars while still close to the ZAMS, most relatively fast-rotating stars will only develop Be characteristics during their latest stages in the MS, as they approach $\Omega/\Omega_{\rm crit} \approx 1$.

If we could assume that all Be stars rotate at $\Omega/\Omega_{\rm crit} \approx 1$, it would be very easy to explain the Be phenomenon. However, observational evidence against this hypothesis remains strong. After correcting for the effects of gravity darkening, Frémat et al. (2005) conclude that, on average, Be stars rotate at $\Omega = 0.88\Omega_{\rm crit}$. However, this average hides large variations. From a statistical analysis of the equatorial rotation rates of classical Be stars, Cranmer (2005) concludes that early Be stars rotate at significantly subcritical speeds. It can be argued that $\Omega_{\rm crit}$ is perhaps not the physical magnitude relevant to this problem, but still it seems clear that early B-type stars in general and early Be stars in particular seem to rotate at significantly lower $\Omega/\Omega_{\rm crit}$ rates than their late-type counterparts. As a matter of fact, the rotational velocity distributions for early and late B-type stars have markedly different shapes (Abt et al. 2002), with a much higher fraction of slow rotators among early B-type stars.

3. The binary channel for the formation of Be stars

3.1. Be stars in binaries

Harmanec et al. (2002) have proposed that all Be stars are members of binary systems and that their disks are built from material lost to the gravitational pull of the companion. Such model is not accepted as a general explanation, but the existence of Be/X-ray binaries (X-ray sources composed of a Be star orbited by a neutron star) demonstrates that binarity may indeed play a role (if rather different) in the origin of the Be phenomenon: some Be stars have at a previous stage received mass (and angular momentum) from a binary companion.

According to the standard model, most (if not all) Be/X-ray binaries have formed via the same standard evolutionary channel. The progenitor is an intermediate-mass close binary with moderate mass ratio $q \gtrsim 0.5$. The original primary starts transferring mass to its companion when it swells after the

end of the hydrogen core burning phase (case B). Mass transfer results in a helium star and a rejuvenated main sequence (MS) star. If the helium star is massive enough, it will undergo a supernova explosion and become a neutron star. If the binary is not disrupted, it may emerge as a Be/X-ray binary.

This model has been developed in a number of references, among which, Habets (1987), Pols et al. (1991), Portegies Zwart (1995) and Van Bever & Vanbeveren (1997). All these models assume that the original primary must have a mass $\gtrsim 12\,M_{\odot}$ (because otherwise it would not produce a neutron star) and that the original secondary receives an important amount of mass and angular momentum from its companion. There is an implicit, but fundamental, assumption hidden in this argument: the Be nature of the original secondary is due to accretion of high-angular-momentum material from the primary. However, there has been no attempt at explaining how this is achieved. Of course, if near-critical rotation is a *sufficient* condition for having a Be star, then there is no need to provide a mechanism, because it has been amply demonstrated that accretion of even a small amount of material (on the order of $0.1M_{\odot}$) is enough to spin up the star to critical rotational velocity (e.g., Packet 1981).

Be stars in Be/X-ray binaries do not seem different from isolated Be stars in any fundamental way. Ample evidence has conclusively shown that their disks may disappear and then reform from the inside (e.g., Telting et al. 1998; Negueruela et al. 2001). As they have likely accreted a large amount of matter, their internal structure may have been slightly affected (cf. Braun & Langer 1995), but their observed characteristics differ from those of isolated Be stars only in ways that can be perfectly explained by the effect of the orbiting neutron star on the circumstellar disk. As detailed by Okazaki & Negueruela (2001), the presence of a neutron star companion results in the truncation of the decretion disk and the accumulation of material inside the truncation radius. This leads to higher densities than in the disks of isolated Be stars, a fact that seems to be confirmed by observations (Reig et al. 1997; Zamanov et al. 2001). Okazaki & Hayasaki (these proceedings) provide a review of our understanding of the complex interaction between the Be envelope and the neutron star.

While Be/X-ray binaries are relatively easy to find, because of their hard X-ray emission, they are not the only examples of Be stars formed through mass transfer. As discussed below, other Be stars are believed to correspond to different stages in this evolutionary path. Moreover, if the predictions of population synthesis models are correct, many Be stars formed by mass transfer in a binary may not be detectable as binaries, either because they have eventually lost the remnant of the original primary, as may happen in a supernova explosion, or because the mass ratio is large and the effect of the low-mass companion on the spectrum of the Be star will be small and very difficult to observe.

3.2. The rule or the exception?

Be/X-ray binaries are very obvious representatives of the fact that Be stars can be produced via binary evolution. The theoretical evolutionary path developed to explain their formation is reinforced by observations showing interacting binaries that can be identified with different stages along this path. Just to quote a few examples from the literature, **V380 Cyg** is a binary with a B1.5 II-III ($14M_{\odot}$, $17R_{\odot}$) primary close to filling its Roche lobe and a B2 V ($8M_{\odot}$,$4R_{\odot}$)

secondary (Hill & Batten 1984). This is an example of pre-contact system that has not started mass transfer yet. **RY Per** is a binary undergoing mass transfer from an F7: II-III ($1.6M_{\odot}$, $8R_{\odot}$) donor star onto a very fast rotating B4: V companion ($6M_{\odot}$, $8R_{\odot}$), which is already rather more massive than the donor (Olsen & Plavec 1997). **HD 45166** is composed by a B7 V star and a very unusual secondary of about the same mass, which Steiner & Oliveira (2005) classify as quasi-WR. This could be an example of an exposed He core. Finally, the B0.5 Ve star ϕ **Persei** is one of the best known examples of a post-mass transfer system, as it is orbited by a low-mass sdO subdwarf, believed to be the remnant of the original primary (Gies et al. 1998). A few other Be stars are suspected of hosting subdwarf companions.

Thus all the phases in the path to a Be/X-ray binary are well documented. However, it is important to remember that, while in Be/X-ray binaries the originally more massive star loses a high fraction of its initial mass and is finally reduced to a compact object, other evolutionary paths may involve mass transfer and result in different outcomes. The mass donor does not need to pass a substantial fraction of its mass to the mass gainer in order to spin it to high Ω. A system like AI Cru, which contains a B2 IVe ($10M_{\odot}$, $5R_{\odot}$) primary and a B4: V secondary ($6M_{\odot}$, $4R_{\odot}$) is believed to have experienced a previous phase of mass transfer in which only a fraction of the envelope of the originally more massive star was transfered (Bell et al. 1987).

Summarising, observations clearly indicate that the binary channel contributes to the formation of Be stars and we have reasons to believe that the intrinsic properties of these Be stars are indistinguishable from those of any other Be stars. A direct application of Occam's razor would suggest that, once we have found a channel to produce Be stars, we can safely assume that it is the only channel needed. Again, this assumption fundamentally depends on the issue of critical rotation. If having a star rotating at $\Omega_{\rm crit}$ is a *sufficient* condition for having a Be star, it does not really matter how this critical rotation is achieved. If it is not, then we have not really provided a mechanism for making Be stars, but simply assumed that they form after mass transfer.

Additional indirect evidence supporting an important contribution of the binary channel to the formation of Be stars has been presented by Gies (2001). However, this is not a generally accepted idea, because of two reasons. On the one hand, there is little observational evidence to support the idea that all (or even most) Be stars have binary companions. On the other hand, modern population synthesis models predict that the fraction of stars that have been through a mass transfer phase is small (or very small) compared to the number of Be stars (e.g., Van Bever & Vanbeveren 1997). According to these models, $\sim 4\%$ of B-type stars should experience mass transfer in a binary and so an even smaller fraction are expected to be Be stars formed through mass exchange. This is very far from the $\sim 10-20\%$ (depending on spectral type) of Be stars amongst B-type stars in the Bright Star Catalog (cf. Zorec & Briot 1997).

Against this, McSwain & Gies (2005b), based on a comprehensive photometric study of Be stars in a large sample of open clusters, argue that the true Be/B fraction in the Galaxy is $\lesssim 5\%$ and speculate that the high fraction among bright B-type stars may be due to a selection effect related to the age of Gould's Belt. Moreover, they claim that the position of Be stars in the HR diagrams of

open clusters indicates that a substantial fraction of them are created through binary evolution. The discrepancy between the Be fraction in Galactic open clusters found by McSwain & Gies (2005b) and the statistics of bright field Be stars may perhaps simply stem from the fact that McSwain & Gies (2005b) only consider Be stars *at a given time*, while Zorec & Briot (1997) use the historical record. However, Martayan et al. (2006) find a Be/B fraction $\sim 15-20\%$ for early B types in the LMC field, forcing us to conclude that the true Be/B fraction is not well known at this point and the ability of population synthesis models to reproduce it is still an open subject.

In addition, all population synthesis models predict that a significant fraction of the Be stars created through the binary channel must contain a white dwarf (WD) as the remnant of the originally more massive star (e.g., Van Bever & Vanbeveren 1997; Raguzova 2001). In spite of dedicated searches, so far no convincing candidate has been found for a Be + WD binary (Motch et al. 2006). A certain number of Be stars are known to have low mass companions whose nature is uncertain due to the lack of spectral signatures. Some of them might be WDs, but until definite examples of Be + WD binaries are identified, population synthesis models remain suspect.

4. Rapid rotation in open clusters

A number of works have provided evidence in the sense that OB stars in clusters rotate on average faster than those in the field. Different explanations for this effect have been presented, some of them invoking physical causes, with others trying to understand it as a selection effect.

Gies & Huang (2004) argue that OB stars brake during their evolution, resulting in lower Ω for evolved stars. If the field population is on average older than the clusters surveyed, it may contain more slow rotators. Conversely, Keller (2004) argues that stars in clusters rotate faster because the bright members generally observed are stars close to the turnoff undergoing spin-up at the end of their MS lifetime. Other interpretations do not resort to evolutionary hypotheses, but attribute this effect to the initial conditions. Guthrie (1984) speculated that perhaps the bulk of the field population originated in low density regions in the outskirts of OB associations, where the formation of slow rotators may be favoured.

A similar line of argument is followed by Strom et al. (2005). Recent work has convincingly shown that very high accretion rates are necessary for the formation of massive stars (Behrend & Maeder 2001; Yorke & Sonnhalter 2002). These high accretion rates are easier to attain near the cores of massive clusters, induced by high gas pressure (McKee & Tan 2003). As a consequence, stars formed in massive clusters are more likely to be born with high Ω. In order to test this hypothesis, Strom et al. (2005) have measured the rotational velocities for a large sample of stars in the massive twin clusters h & χ Persei and compared them to the rotational velocities of a sample of field stars selected on the basis that they occupy the same positions in the β/c_0 diagram (and consequently are in the same evolutionary stage) as the cluster stars.

The results of Strom et al. (2005) have challenged many long-held assumptions. They find that the distribution of rotational velocities for mid and late

B-types among members of h & χ Persei is *very* different from the distribution among field stars of the same age, mainly because of an almost complete absence of slow rotators among cluster members. The difference between the Ω distribution of cluster and field stars decreases for earlier spectral types to the point that it is not statistically significant for stars earlier than B2.

According to Strom et al. (2005), these results imply that fast rotation in clusters is primordial and not due to an evolutionary effect, with mid- and late-B stars in clusters being born rotating faster than field stars of the same mass. The observations are interpreted within the context of the magneto-centrifugal model for pre-MS stars (Shu et al. 1994). The rotational velocity of the protostar will be fixed by the interaction between its accretion disk and its magnetic field. For a given magnetic field, higher accretion rates will result in higher rotational velocities, favouring fast rotators in massive clusters. Moreover, mid-B stars have a large radius at the birth line because of the onset of deuterium shell burning and spin up considerably during their descent to the ZAMS .

The implications for early B stars are not so clear. Strom et al. (2005) take their observational result at face value and conclude that early B stars in clusters do not rotate faster than field stars of the same mass. However, it must be noted that all the stars in h & χ Persei with spectral types earlier than B2 are rather evolved and that a significant fraction of them appear to be blue stragglers (Marco et al. 2006). As models for angular momentum transport in fast rotators in the corresponding mass range are still being developed (cf. the non-trivial differences between models in Meynet & Maeder 2000 and Meynet & Maeder 2003), this remains, in my view, an open issue.

5. The evolutionary effect in Be stars

The results of Strom et al. (2005) are conclusive with respect to the Ω distribution in h & χ Persei, but seem difficult to reconcile with the well established fact that Be stars in open clusters are much more frequent among stars evolved away from the ZAMS than among stars still close to the ZAMS. This effect was first remarked by Fabregat & Torrejón (2000), who, based on data collected from the literature for a small sample of clusters, concluded that Be stars were most frequent in clusters with the MS turnoff (MSTO) in the B1 − B2 range (and, correspondingly, ages in the 12 − 24 Myr range).

Keller et al. (1999, 2000) carried out a survey of very populous LMC and SMC clusters in search of Be stars with narrow-band Hα filters. They found large numbers of Be stars, with the highest proportion of Be stars occurring at the earliest spectral types. They also noted a tendency for a higher Be star fraction near the MSTO in most clusters (see also Johnson et al. 2002), though they did not find a clear correlation between cluster age and Be fraction. Later, Keller et al. (2001) also found that most of the Be stars in h & χ Persei were located close to MSTO. The concentration of Be stars close to the MSTO is confirmed in the much larger sample of McSwain & Gies (2005b).

Based on this observational result, Keller et al. (2001) developed the evolutionary model for the Be phenomenon presented in Section 2.1., assuming a direct connection between critical rotation and the onset of the Be phenomenon. As discussed at length in Negueruela et al. (2004), observational evidence shows

that stars with at least $25M_\odot$ can develop the Be phenomenon, but this does not invalidate the basic premise of Keller et al. (2001), as the newer models by Meynet & Maeder (2003) show that $\Omega/\Omega_{\rm crit}$ also increases during the lifetimes of stars with masses in the $\sim 15M_\odot - 25M_\odot$ range.

5.1. Facts and biases

Unlike previous studies, McSwain & Gies (2005b) have observed and analysed a large and statistically significant sample of open clusters using a homogeneous method. It is therefore very significant that their conclusions are rather different from those of other works. They find a much lower Be/B fraction than generally assumed and do not find strong dependences of the Be fraction on several parameters which were generally thought to be relevant.

All these works are based on photometric searches for emission-line stars. Photometric techniques are very efficient at detecting strong Balmer-line emitters, but do not discriminate weak emitters very well (a detailed discussion is presented in McSwain & Gies 2005a). Because of this, they are prone to suffering from several important selection effects. First, it is unlikely that observations may be equally sensitive for early and late B-type stars (late B-type stars in a given cluster may not be surveyed at all if there is a magnitude limit). Moreover, early Be stars tend to be strong emitters, while late Be stars tend to be weak emitters. Both effects conspire to make detection of early Be stars rather easier than the detection of late Be stars.

Perhaps even more importantly, most of the evidence for the Be phenomenon as an evolutionary effect is provided by observations of a few "Be-rich" clusters. Be stars have been searched for in the most populous LMC and SMC clusters (Keller et al. 1999) and in the traditionally-called "Be-rich" clusters in the Galaxy, namely, NGC 663 (Pigulski et al. 2001), h & χ Persei (Keller et al. 2001; Bragg & Kenyon 2002), NGC 3766 (McSwain & Gies 2005a) and NGC 7419 (Pigulski & Kopacki 2000). This pre-selection of *interesting* targets again introduces a discernible bias in the results expectable.

Most of these clusters were surveyed for Be stars precisely because they were known to be rich in Be stars. They are not necessarily representative of the general population, and indeed the results of McSwain & Gies (2005b) suggest that they are not. Moreover, all the "Be-rich" cluster in the Galaxy and most of populous clusters observed in the Magellanic Clouds have ages such that the MSTO is located close to spectral type B2, perhaps explaining the conclusions of Fabregat & Torrejón (2000).

Clear demonstration of the danger of preconceived ideas comes from the double cluster h & χ Persei, generally listed as having a population extremely rich in Be stars (see Fabregat & Torrejón 2000, and references therein). A complete spectroscopic survey of h & χ Persei finds that the fraction of Be stars in these clusters is $\sim 13\%$ among early B-type stars and negligible for stars later than B4 (Bragg & Kenyon 2002). This is not a very high fraction. It is indeed lower than many estimates of the Be fraction for the field population. The double cluster is very massive (Slesnick et al. 2002) and so the high number of Be stars is simply a consequence of the high number of (B-type) stars, not of a high Be/B fraction.

Other open clusters really have a high Be fraction among stars around the MSTO. Classical examples are NGC 663 ($\sim$ 25 Myr), showing $\sim$ 33% for stars earlier than B5 at a given time, NGC 3766 ($\sim$ 25Myr), where a very high fraction of early B-type stars have been seen at some point in a Be phase, and NGC 7419, ($\sim$ 15 Myr), with $> 30\%$ among early B-type stars at a given time (Negueruela et al., these proceedings). However, as discussed above, these clusters may not be representative of the average young open cluster in the solar neighbourhood. For a start, these three clusters are relatively massive. This may not only have an implication on the initial stellar rotational velocities (see Section 4.), but also means that the number of B stars is high enough to make the Be/B fraction statistically significant.

In order to see the significance of a high number of members, let us consider one of the best (if not the best) studied open clusters in the sky, The Pleiades. This cluster has an estimated age of 130 Myr, with the stars around the turnoff having spectral type B6 IV. Out of 15 B-type stars in this cluster, 4 are Be stars (Abt & Levato 1978). At $\sim$ 130Myr, the three B9.5 V stars in the cluster cannot be considered to be very evolved and we can calculate the Be/B fraction for stars close to the MSTO using only spectral type B9 and earlier. This results in 4 Be stars out of 12 B stars or 33%, a percentage as high as in the "Be-rich" clusters. However, the number of stars is too low to accept this result as statistically meaningful. The same happens in many other clusters in the $100-200$ Myr range, which have few B stars left, meaning that we are likely to accept as statistically significant only calculations for massive clusters, which may not be representative of the general population.

In summary, though it seems clear that there is an evolutionary effect such that the Be fraction appears much higher among the (moderately) evolved stars in a population than among the unevolved members, the nature and reasons for this effect cannot be ascertained. Keller et al. (2001) have argued that it is due to the evolution of rotational velocity as the stars age, but McSwain & Gies (2005b) find that the location of Be stars in the HR diagrams of open clusters does not favour this interpretation and Strom et al. (2005) have shown that the Ω distribution among stars in h & χ Persei is exactly the opposite from what this hypothesis would require. Some other mechanism must be required to complement (or completely replace) Ω evolution. McSwain & Gies (2005b) suggest that this may be mass transfer in a close binary, but again this model is not without complications.

Finally, in spite of the evidence accumulated for the existence of this evolutionary effect, there appears to be a non-negligible fraction of Be star very close to the ZAMS (cf. Wisniewski et al., these proceedings, and see also Zorec et al. 2005). Wisniewski et al. find substantial numbers of Be stars in clusters younger than 10 Myr old, while some good examples of Be stars with early spectral types in open clusters in the $3-10$ Myr range exist. Such objects are very likely incompatible with mass transfer in a binary system. Zorec et al. (2005) try to reconstruct the evolutionary status of a sample of Be stars and come to the conclusion that early B-type stars (with $M \gtrsim 12M_{\odot}$) may display the phenomenon at any stage during their MS life, but less massive stars only become Be stars after a significant fraction ($\sim$ 0.5) of their lifetime. Once again, if the Be phenomenon may simply be equated with having $\Omega/\Omega_{\rm crit} \approx 1$, many different

channels may contribute to the population. If this is not the relevant condition, the evolutionary effect in Be stars is still very far from being understood.

5.2. Metallicity and the Be phenomenon

From a study of data in the literature, Maeder et al. (1999) found that the fraction of Be stars increases with decreasing metallicity (Z). However, their work used the populous SMC clusters as representative of the low-Z environment, thus introducing a likely bias. From a more homogeneous study, Wisniewski et al. (these proceedings) find a dependence of the Be fraction with Z, though not as strong as suggested by Maeder et al. (1999). McSwain & Gies (2005b) find suggestive, but not compelling, evidence for a higher Be fraction among clusters outside the Solar Circle than among clusters inside it, again suggesting some sort of weak dependence of the Be fraction on Z.

The reasons for this dependence are not obvious. Among massive stars, lower Z will result in weaker stellar winds. According to evolutionary models (e.g., Meynet & Maeder 2000), the stellar wind is very efficient at removing angular momentum from a star of solar metallicity, but not so much at SMC metallicities. As a result, solar metallicity stars will spin down during their lifetime much more significantly than lower Z stars. This will translate into a higher fraction of fast rotators. Indeed Keller (2004) finds that stars in a sample of LMC early-B objects rotate faster (at almost 2-σ significance) than stars in a sample of early-B objects in Galactic open clusters. However, as the higher Be fraction at lower Z is not confined to the earliest spectral types, but seems to extend to lower mass B stars, with luminosities incapable of sustaining a radiative wind, the absence of wind braking cannot be the main cause of the increased Be fraction at low Z.

Perhaps the initial conditions for star formation result in higher average Ω at lower Z, though the reasons for this remain unexplored. In any case, the dependence of the Be fraction on Z is not yet ascertained. Martayan et al. (2006) find a comparable Be fraction among the LMC field population and in the Solar neighbourhood. An even more striking cautionary example is provided by two relatively massive clusters in the Cas OB8 association. This group consists of at least five open clusters known to have similar ages and distance estimates, situated in a relatively small area of the sky. As such, they are expected to have been formed in a single episode of star formation, probably because of the fragmentation of a giant molecular cloud.

The most massive cluster in Cas OB8 is NGC 663 (Marco et al. 2006). A spectroscopic survey of 150 likely members was conducted by Negueruela et al. (2005) in October 2002. At that time, about one third of all stars earlier than B5 V were in the Be phase, with little variation between evolved (giants and subgiants) and MS stars. The second most massive cluster in Cas OB8 is NGC 654. Shi & Hu (1999) carried out a spectroscopic survey observing more than 40 B-type members down to spectral type B4 V. Near the cluster core, where all the objects down to a given magnitude were observed, they found 2 Be stars out of 34 early-type B stars. The fact that two clusters likely to have formed at the same time from the same material have extremely different Be/B fractions suggests that chemical composition is not the main factor affecting the eventual appearance of a large population of Be stars.

6. Conclusions

Though the study of large populations of early type stars in open clusters seems to be the only way to gain an understanding of the causes and incidence of the Be phenomenon, data so far has provided a very blurred and, in many aspects, contradictory picture

We know for certain that some fraction of Be stars must have undergone mass transfer in a binary system and we have reasons to suspect that their Be nature may be in some way due to this process. However, different authors have provided completely divergent estimates of the contribution of this binary channel to the formation of Be stars. In my opinion, the lack of evidence for any companion in many Be stars, together with the statistics of the Be fraction and star counts in clusters, make it unlikely that most Be stars form through this channel. On the other hand, I believe that present evidence suggests that a non-negligible fraction of Be stars form in this way.

Several works have shown that B-type stars in (at least massive) open clusters rotate faster than those in the field. This fast rotation is likely to be primordial and related to the initial conditions of star formation, as seems to be confirmed by the results of Strom et al. (2005). It is, however, interesting to note that in the case of h & χ Persei, this higher average Ω has not *yet* resulted in a high Be fraction.

There is abundant evidence demonstrating that Be stars in open clusters are more numerous around the MSTO, suggesting some sort of evolutionary effect, but claims of a preferred age with a higher fraction of Be stars are likely based on biased samples. There is also some evidence favouring an inverse dependence of the Be fraction on metallicity. However, at this point we do not really understand which mechanism(s) may cause this dependence. The fact that the fraction of Be stars varies enormously from cluster to cluster, even at a given Z, strongly suggests that the conditions leading to the development of the Be phenomenon must be primordial and have to be found at the cluster level.

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